The Araucaria Project. Near-Infrared Photometry of Cepheid Variables in the Sculptor Galaxy NGC 55 [1]

Wolfgang Gieren
Universidad de Concepción, Departamento de Fisica, Astronomy Group, Casilla 160-C, Concepción, Chile

Grzegorz Pietrzyński
Universidad de Concepción, Departamento de Fisica, Astronomy Group, Casilla 160-C, Concepción, Chile
Warsaw University Observatory, Al. Ujazdowskie 4, 00-478, Warsaw, Poland

Igor Soszyński
Universidad de Concepción, Departamento de Fisica, Astronomy Group, Casilla 160-C, Concepción, Chile
Warsaw University Observatory, Al. Ujazdowskie 4, 00-478, Warsaw, Poland

Fabio Bresolin
Institute for Astronomy, University of Hawaii at Manoa, 2680 Woodlawn Drive, Honolulu HI 96822, USA

Rolf-Peter Kudritzki
Institute for Astronomy, University of Hawaii at Manoa, 2680 Woodlawn Drive, Honolulu HI 96822, USA

Jesper Storm
Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany

Dante Minniti
Departamento de Astronomia y Astrofisica, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile

arXiv:0709.2421v1 [astro-ph] 15 Sep 2007

ABSTRACT

We have obtained deep images in the near-infrared J and K filters of four fields in the Sculptor Group spiral galaxy NGC 55 with the ESO VLT and ISAAC camera. For 40 long-period Cepheid variables in these fields which were

[1]Based on observations obtained with the ESO VLT for Large Programme 171.D-0004

recently discovered by Pietrzyński et al., we have determined mean J and K magnitudes from observations at two epochs, and derived distance moduli from the observed PL relations in these bands. Using these values together with the previously measured distance moduli in the optical V and I bands, we have determined a total mean reddening of the NGC 55 Cepheids of E(B-V)=0.127 $\pm$ 0.019 mag, which is mostly produced inside NGC 55 itself. For the true distance modulus of the galaxy, our multiwavelength analysis yields a value of 26.434 $\pm$ 0.037 mag (random error), corresponding to a distance of 1.94 $\pm$ 0.03 Mpc. This value is tied to an adopted true LMC distance modulus of 18.50 mag. The systematic uncertainty of our derived Cepheid distance to NGC 55 (apart from the uncertainty on the adopted LMC distance) is $\pm$4%, with the main contribution likely to come from the effect of blending of some of the Cepheids with unresolved companion stars. The distance of NGC 55 derived from our multiwavelength Cepheid analysis agrees within the errors with the distance of NGC 300, strengthening the case for a physical association of these two Sculptor Group galaxies.

Subject headings: distance scale - galaxies: distances and redshifts - galaxies: individual(NGC 55) - stars: Cepheids - infrared photometry

1. Introduction

The effectiveness of using multiwavelength optical and near-infrared (NIR) observations of Cepheid variables for distance determination of galaxies has been known for a long time (McGonegal et al. 1982; Madore & Freedman 1991). Only recently however the technical problems with obtaining accurate and reliable NIR photometry for faint objects in dense regions have been solved. Using NIR observations of Cepheids provides a number of advantages for accurate distance work. First, the total and differential reddening is significantly reduced in comparison to the optical bandpasses. Second, the Cepheid PL relation becomes steeper toward longer wavelengths, and its intrinsic dispersion becomes smaller, both factors helping in deriving a more accurate distance. Third, metallicity effects on the PL relation in the near-IR are expected to be less important than at optical wavelengths (Bono et al. 1999). Fourth, and very importantly from an observational point of view, the amplitudes of variability are significantly smaller in the NIR than at optical wavelengths, so even random single-epoch observations approximate the mean magnitude reasonably well. If the period and optical light curve of a Cepheid is accurately known, it is

possible to derive its mean magnitude in the NIR bands with an impressive 1-2% accuracy from just one single-epoch observation (Soszyński et al. 2005).

Simultaneously studying NIR and optical PL relations of Cepheids provides another important advantage. By combining the observed distance moduli in the optical and NIR it is possible to derive both the total reddening and the true distance modulus with very high accuracy. This has been demonstrated in the previous papers of this series which reported the distances to NGC 300 (Gieren et al. 2005a), IC 1613 (Pietrzyński et al. 2006a), NGC 6822 (Gieren et al. 2006) and NGC 3109 (Soszyński et al. 2006) derived by this method. For all these galaxies, we were able to determine their distances with respect to the LMC with a $\sim$3% accuracy from our technique. The multiband closure on the total reddening estimates, through the use of the Wesenheit function and near-infrared data, has made it possible to achieve these accuracies.

NGC 55 is a highly inclined late-type galaxy classified as SB(s)m in the NASA/IPAC Extragalactic Database. It bears some resemblance to the LMC and is one of the approximately 30 known members of the Sculptor Group (Jerjen et al. 2000). NGC 55 was included in the list of target galaxies of our ongoing Araucaria Project (Gieren et al. 2005b) because of its relative proximity which allows accurate photometry and spectroscopy of the different stellar distance indicators scrutinized in our project, and because existing oxygen abundance determinations from H II regions indicate a low metallicity of about 0.25 solar, close to the SMC (e.g. Lee et al. 2006, and references therein) which makes NGC 55 the lowest-metallicity spiral galaxy in our sample. This is important because one of our main goals in the Araucaria Project is to determine the effect of metallicity on the various stellar methods of distance determination we are investigating. Also, color images of NGC 55 clearly suggested the existence of an abundant young stellar population in this galaxy, suggesting the presence of abundant blue supergiant and Cepheid populations, both types of objects being very useful for distance determination. In fact, we have discovered more than 100 blue supergiants in NGC 55 and have obtained low-resolution spectra for abundance analysis with VLT/FORS. The abundance results we will obtain from these data will give us an opportunity of independently check on the nebular oxygen abundances, and will allow us to determine the distance of the galaxy with the Flux-Weighted Gravity-Luminosity Relation introduced by Kudritzki et al. (2003).

There are several distance determinations to NGC 55 based on different methods in the literature, which have been collected in Table 4. They will be briefly discussed in section 4. These previous distance estimates have yielded results which range from 1.34 Mpc (Pritchet et al. 1987) to 2.30 Mpc (Van de Steene et al. 2006). This considerable discrepancy hints at relatively large errors in one or several of these previous determinations, and a

more accurate distance determination was therefore clearly desirable. Since no previous surveys for Cepheid variables had been conducted in NGC 55, we have carried out such a wide-field Cepheid survey in optical V and I filters which resulted in the discovery of 143 Cepheids (Pietrzyński et al. 2006b; hereafter Paper I). From 130 Cepheids with periods longer than 10 days, we constructed PL relations in V, I and the reddening-independent (V-I) Wesenheit band, yielding as a best estimate of the distance to NGC 55 a value of 1.91 $\pm$ 0.10 Mpc.In this paper, we extend the light curve coverage for 40 Cepheids in NGC 55 to the NIR J and K bands. We then utilize the multiband VIJK data for these stars for an accurate determination of the total (average) interstellar extinction to the Cepheids in NGC 55, and determine an improved distance to the galaxy. As mentioned above, the extension of the Cepheid work to the NIR is a fundamental step to reduce the systematic error in the Cepheid distance, mostly by decreasing the sensitivity of the result to reddening and effects of metallicity on the period-luminosity relation.

The paper is composed as follows. In section 2 we describe the NIR observations, data reductions and calibration of our photometry. In section 3 we derive the J- and K-band Cepheid PL relations in NGC 55 from our data and determine the true distance modulus to NGC 55 from a multiwavelength analysis. In section 4, we discuss our results, and in section 5 we summarize our conclusions.

2. Observations, Data Reduction and Calibration

We used deep J- and K-band images recorded with the 8.2 m ESO Very Large Telescope equipped with the Infrared Spectrometer and Array Camera (ISAAC). Figure 1 shows the location of the four 2.5 x 2.5 arcmin fields observed in service mode on 7 nights between 18-07-2004 and 21-09-2004. The coordinates of the field centers were chosen in such a way as to maximize the number of Cepheid variables observed and optimize their period distribution. Each field was observed in both NIR bands two times, on two different nights, and therefore at different pulsation phases of the Cepheids in these fields. The observations were carried out using a dithering technique, with a dithering of the frames following a random pattern characterized by typical offsets of 15 arcsec. The final frames in the J and K bands were obtained as a co-addition of 24 and 164 single exposures obtained with integration times of 30 and 15 s, respectively. Thus, the total exposure time for a given observation was 12 minutes in J and 41 minutes in K. The observations were obtained under excellent seeing conditions, typically around 0.5 arcsec. Standard stars on the UKIRT system (Hawarden et al. 2001) were observed along with the science exposures to allow an accurate transformation of the instrumental magnitudes to the standard system.

The images were reduced using the program JITTER from the ECLIPSE package developed by ESO to reduce near-IR data. The point-spread function (PSF) photometry was carried out with the DAOPHOT and ALLSTAR programs. The PSF model was derived iteratively from 20 to 30 isolated bright stars following the procedure described by Pietrzyński et al. (2002). In order to convert our profile photometry to the aperture system, aperture corrections were computed using the same stars as those used for the calculation of the PSF model. The median of the aperture corrections obtained for all these stars was finally adopted as the aperture correction for a given frame. The aperture photometry for the standard stars was performed with DAOPHOT using the same aperture as the one adopted for the calculation of the aperture corrections.

The astrometric solution for the observed fields was performed by cross-identification of the brightest stars in each field with the Infrared Digitized Sky Survey 2 (DSS2-infrared) images. We used programs developed by Udalski et al. (1998) to calculate the transformations between the pixel grid of our images and equatorial coordinates of the DSS astrometric system. The internal error of the transformation is less than 0.3 arcsec, but systematic errors of the DSS coordinates can be up to about 0.7 arcsec.

In order to perform an external check on our photometric zero points, we tried to compare the magnitudes of stars in the 2MASS Point Source Catalog located in our NGC 55 fields with our own photometry. Unfortunately, even the brightest stars in our dataset whose photometry is not affected by nonlinearity problems are still very close to the faint magnitude limit of the 2MASS catalog and have 2MASS magnitudes with formal errors of $\sim$0.2 mag. Moreover, all our NGC 55 fields are located in regions of high stellar density (see Figure 1), and most of the 2MASS stars turn out to be severely blended as seen at the higher resolution of our VLT/ISAAC images. It was therefore not possible to carry out a reliable comparison of the two photometries. However, since our reduction and calibration procedure is extremely stable, we should have achieved the same typical zero point accuracy we were able to achieve in the previous near-infrared studies of Local Group galaxies where a comparison with 2MASS magnitudes for a common set of stars was possible. From this argument, we expect that our photometric zero points are determined to better than $\pm$0.03 mag in both J and K filters.

Our four fields in NGC 55 contain a subset of 40 of the 143 Cepheids reported in Paper I. All individual observations in J and K we obtained are presented in Table 1 which lists the star's IDs, heliocentric Julian day of the observations, and the measurements in J and K with their standard deviations. For most of the Cepheids we collected two observations per given filter. For some objects we obtained only one observation in the J or K band as a consequence of the locations of these objects close to the edge of the observed field.

3. Near-Infrared Period-Luminosity Relations

All individual J and K measurements reported in Table 1 were transformed to the mean magnitudes of the Cepheids using the recipe given by Soszyński et al. (2005). The corrections to derive the mean magnitudes from the observed random-phase magnitudes were calculated by taking advantage of the complete V- and I-band light curves from Paper I, exactly in the way as described in the Soszyński et al. paper. For the vast majority of the Cepheids, the mean J and K magnitudes determined from the two individual random-phase magnitudes agree very well. We were helped by the fact that the optical observations in Paper I, and the near-IR followup observations reported in this paper have been obtained relatively close in time (1-2 years), reducing the effect inaccurate periods will have on the calculations of the phases of the NIR observations. For most of our objects, the difference between the mean magnitudes derived from the two independent random-phase JK measurements was comparable to the standard deviations of the individual observations.

Table 2 gives the intensity mean J and K magnitudes of the individual Cepheids. Each value was calculated as the average of the individual determinations of the mean magnitude. In Table 2 we also provide the periods (from Paper I) and uncertainties on the mean magnitudes (which contain the contribution of a 0.03 mag intrinsic error coming from the transformation of the random-phase to the mean magnitudes; see Soszyński et al. 2005).

In Figure 2 we show the J- and K-band period-mean magnitude diagrams defined by the NGC 55 Cepheids in our observed fields. From the 40 stars in these diagrams, we excluded 10 objects from the final distance solution; these stars are plotted as open circles in Fig. 2, with their IDs indicated. We excluded these objects from our distance analysis for the reasons given in the following. Variables cep001, cep002 and cep004 have extremely long periods of 176, 152 and 98 days. Cepheids of such long periods, and the corresponding very high luminosities, have long been suspected to deviate from the extension of the linear PL relation defined by Cepheids of shorter periods, in the sense that they are becoming intrinsically fainter than what the linear PL relation would suggest. The empirical evidence for this effect has been discussed by a number of authors (e.g. Gieren et al. 2004; Madore & Freedman 1991). The position of the three longest-period Cepheids in our sample suggests that the same effect is present in our data, and we therefore prefer to exclude these objects from the distance solution. Particularly cep004 at P=98 days is very underluminous in the J band, whereas in K it is closer to the ridge line. A possible explanation for this behavior is that this variable suffers excessive reddening. This would be consistent with its young age, as derived from a period-age relation (e.g. Bono et al. 2005), which implies that such a long-period Cepheid must still be close to the molecular cloud where it was formed. An

additional reason to exclude Cepheids with periods longer than 100 days in our solution is the fact that the fiducial LMC PL relation has not been calibrated with such long-period stars either. The adopted procedure to introduce an upper period cutoff at 100 days is also consistent with our previous Cepheid distance work in the Araucaria Project.

Three Cepheids (cep113, cep086 and cep036) are more than one full magnitude brighter in K than the ridge line luminosities at the corresponding periods, and it seems likely that these stars are strongly blended by very red objects. This is supported by the observation that these objects are still over-luminous in the J-band PL relation, but by a smaller amount than in K (lower panel of Fig. 2). All three objects fall very clearly outside the instability strip on the K, J-K CMD, which is shown in Fig. 3, supporting the idea that they are either not classical Cepheids, or stars suffering strong observational anomalies. The images of these three stars obtained on the nights of best seeing do indeed suggest the presence of bright companion stars which are not quite resolved. Yet, it is also possible that these very luminous variables are a different kind of objects, and not blended Cepheids. They are bright enough for near-IR spectroscopy, which would shed more light on the true nature of these objects. Whatever the correct explanation will turn out to be for their excessive brightness, we believe it to be the correct procedure to exclude them from the distance solution. Stars cep079, cep033 and cep013 show very strange PSF profiles which are likely to be caused by unresolved companion stars as well, consistent with their very bright apparent magnitudes, for their respective periods. The only Cepheid we have excluded from the sample without having a specific reason other than its strong deviation, particularly in the K band, from the ridge line is cep023. In K, this object is 1 mag fainter than the ridge line at this period, with a similar effect in the J band. Perhaps cep023 is not a classical Cepheid. It could also be an excessively reddened Cepheid. Below, we show that our distance solution is rather insensitive to the final choice of the sample we are using for the determination of the distance of NGC 55.

In Fig. 4, we plot the PL diagrams in J and K for the adopted final sample of 30 Cepheids. Least-squares fits to a line yield slopes of -2.933 $\pm$ 0.133 in K, and -2.843 $\pm$ 0.165 in J, respectively. These slopes are shallower than, but within 2 σ consistent with the slopes of the Cepheid PL relations in the LMC, which are -3.261 in K, and -3.153 in J (Persson et al. 2004). Following the procedure we have used in our previous papers, we adopt the LMC slopes of Persson et al. (2004) in our fits. This yields the following PL relations for NGC 55:

$$J = -3.153 \log P + (24.395 \pm 0.048) \qquad \sigma = 0.265$$

K = -3.261 log P + (23.975 ± 0.041) $\sigma = 0.223$

The zero points in these relations are very little sensitive to our adopted exclusion of suspect objects. If we retain all 37 Cepheids in the fits except the very strongly and definitively blended objects cep113, cep086 and cep036 (which in the K band are more than a full magnitude brighter than the ridge line luminosity at the respective periods), and even including the Cepheids with periods longer than 100 days, the zero points change only slightly to 24.433 in J and 23.996 in K. However, the uncertainties of the zero points increase substantially, and the dispersions of the PL relations in J and K now increase to 0.405 mag and 0.377 mag, respectively. We are confident that we have cleaned our raw sample of Cepheids in the best possible way to obtain the most reliable values for the zero points of the J- and K-band PL relations, and their uncertainties from our datasets.

In order to determine the relative distance moduli between NGC 55 and the LMC, we need to convert the NICMOS (LCO) photometric system used by Persson et al. (2004) to the UKIRT system utilized in this paper. According to Hawarden et al. (2001), there are just zero point offsets between the UKIRT and NICMOS systems (e.g. no color dependences) in the J and K filters, which amount to 0.034 and 0.015 mag, respectively. Applying these offsets, and assuming an LMC true distance modulus of 18.50 as in our previous work in the Araucaria Project, we derive distance moduli for NGC 55 of 26.593 ± 0.048 mag in the J band, and 26.454 ± 0.041 mag in the K band.

As in our previous papers in this series, we adopt the extinction law of Schlegel et al. (1998) and fit a straight line to the relation $(m-M)_0 = (m-M)_\lambda - A_\lambda = (m-M)_\lambda - E(B-V) * R_\lambda$. Using the distance moduli in the V and I photometric bands derived in Paper I together with the values for the J and K bands calculated above, we obtain for the reddening and the true distance modulus of NGC 55 the following values:

$$E(B-V) = 0.127 \pm 0.019$$

$$(m-M)_0 = 26.434 \pm 0.037,$$

corresponding to a distance of NGC 55 of 1.94 ± 0.03 Mpc.

In Table 3 we give the adopted values of R_λ and the unreddened distance moduli in each band which are obtained with the reddening value determined in our multi-wavelength approach. The agreement between the de-reddened distance moduli in each band is excellent. In Fig. 5, we plot the apparent distance moduli in VIJK as a function of R_λ, and the best fitting straight line to the data; it is appreciated that the total reddening, and the

true distance modulus of NGC 55 are very well determined from this fit.

4. Discussion

Our new distance to NGC 55 derived from optical/near-infrared photometry of Cepheids in this galaxy agrees within the combined 1 σ uncertainties with the previous determination from the Tully-Fisher method (Karachentsev et al. 2003), the I-band magnitude of the tip of the red giant branch as derived from HST WFPC2/ACS images (Tikhonov et al. 2005), and with the PNLF distance derived by Van de Steene et al. (2006). Whereas the quoted uncertainty of the TRGB distance is only slightly larger than the Cepheid distance obtained in this paper, the distances coming from the TF and PNLF methods are clearly considerably more uncertain. The most discrepant distance determination from carbon stars in NGC 55 of Pritchet et al. (1987) has probably the largest systematic uncertainty, due to both the use of a non-reliable distance indicator, and of an inadequate spatial resolution of 0.59 arcsec/pixel in their CCD images. The short distance to NGC 55 they derive is likely the result of a strong blending of some of their target carbon stars by nearby stars not resolved in their photometry. The quopted $\pm$ 0.08 Mpc distance uncertainty obviously refers to an intrinsic error and does not account for the systematic uncertainty in this measurement.

An exhaustive discussion of the systematic errors which may affect the Cepheid distances derived with our multiwavelength technique was presented in the papers of Gieren et al. (2005a, 2006), and Pietrzyński et al. (2006a) which discussed the multiband Cepheid distance analyses for NGC 300, NGC 6822 and IC 1613. Here we discuss only the most important and specific issues concerning NGC 55. First of all, we have been able to use a number of Cepheids in our present study which is large enough to reduce the effect of a possible inhomogeneous filling of the Cepheid instability strip to a level that its expected effect on the distance of NGC 55 is insignificant (particularly as our current results from the NIR are combined with the distance results from the previous optical study in Paper I which were based on more than 100 Cepheid variables). Also, the removal of outliers is not critical in this study-for all but one object we have excluded from the sample we adopted for the distance determination we had strong reasons for the exclusion, and even retaining all objects with the exception of three blends which are recognized as such from our images produces a change in the distance which is less than 2%.

The near-infrared photometry of this paper has confirmed the distance we had derived in Paper I from the reddening-independent (V-I) Wesenheit magnitude within $\pm$2%. Given the high inclination of NGC 55 with respect to the line of sight and the clear possibility of

relatively strong and variable reddening of the Cepheids in this galaxy, it was imperative to confirm the results from the Wesenheit index with near-IR photometry. The results of this paper summarized in Table 3 and Figure 5 suggest that any residual effect of reddening on the distance of NGC 55 determined in this paper is negligible. The importance of this cannot be overstated because in most Cepheid-based distance determinations of late-type galaxies, particularly when infrared data are sparse or not available, intrinsic reddening is likely to be the largest source of systematic error.

Another contributor to the possible systematic error of our present distance result is the effect of metallicity on the Cepheid PL relation. In the galaxies so far studied in our project, including NGC 55, we have not found convincing evidence that the slope of the Cepheid PL relation in optical or near-IR bands is *not* universal. The results of Gieren et al. (2005c) on the Milky Way and LMC Cepheid PL relations from Cepheid distances determined with the infrared surface brightness technique (Fouqué & Gieren 1997) seem to support the scenario of a universal *slope* of the Cepheid PL relation in optical and NIR bands. This is supported by the recent parallax work of Benedict et al. (2007), and van Leeuwen et al. (2007), and also by the very exhaustive recent analysis of Fouqué et al. (2007) which all yield results compatible with a constant slope of the PL relation. However, there is also evidence for a possible non-constancy of the PL relation slope, as the kink at a period of 10 days observed in the LMC PL relation in optical bands (e.g. Ngeow & Kanbur 2006). In the present paper, we find evidence that the slope of the PL relation in NGC 55 in J and K is the same as in other galaxies, strengthening the case for the universality of the PL slope, but this conclusion hinges on the assertion that the objects which are over-bright in K in Fig. 2 are indeed observational anomalies, as discussed in the previous section. Work to settle the question of the universality of the slope of the Cepheid PL relation in a definitive way must certainly continue. We intend to give a much more detailed and quantitative discussion of this issue in a forthcoming paper, and *assume* the constancy of the PL relation slopes in the various bands, as we have done in the previous papers of this series. The extent to which the *zero point* of the PL relation is affected by metallicity is still an open issue and will be addressed in our project once we will have measured the distances to our target galaxies from other methods as well, particularly from the blue supergiant FGLR (Kudritzki et al. 2003), and from the TRGB method. We therefore prefer to leave an exhaustive discussion of this point to a later stage of our project.

As in previous papers in our project, we have applied utmost care to determine the zero points of our photometry as accurately as possible. From the arguments given in section 2 we believe that the zero points are accurate to better than ± 0.03 mag, in both J and K. One issue of concern is the effect of crowding and blending of the target Cepheids in NGC 55 on our results. We were fortunate enough to have images of exquisite quality, obtained under

excellent seeing conditions at our disposal, and we believe that we were able to identify all Cepheids in our sample whose fluxes are significantly affected by nearby companion stars. It is, however, difficult to quantify the remaining effect blending can still have on our distance result as long as we do not have images of our NGC 55 Cepheids obtained at higher angular resolution. As a guide, however, we can use the results we obtained for another Sculptor galaxy, NGC 300. For this galaxy, a comparison of single-epoch HST-ACS photometry with ground-based photometry suggested that the effect of blending affects the distance determination with our method by less than 2% (Bresolin et al. 2005). The effect for NGC 55 should be similar due to its very similar distance, but could be slightly more serious due to its higher inclination, as compared to NGC 300. We assume that 3% is a reasonable upper limit for the possible remaining effect of unresolved stars in the Cepheid photometry on the distance result. The effects acts to make the Cepheids too bright and therefore tends to decrease the distance.

Probably the largest source of systematic uncertainty on our measured distance to NGC 55 is the value of the adopted distance to the LMC of 18.50 mag to which our distance determination is tied. The uncertainty of this value may exceed 10% (Benedict et al. 2002). However, if future work changes the currently adopted LMC distance, we can easily adapt the distances of the target galaxies of our project to the new value. The *relative* distance moduli will remain unaffected.

From this discussion, and from the conclusions about systematic uncertainties presented in the previous papers in this series we conclude that, apart from the systematic uncertainty on the adopted distance to the LMC, the total systematic error on our present distance determination of NGC 55 does not exceed ∼4%. We believe that our combined optical-NIR Cepheid work on NGC 55 has brought about a distance determination to this galaxy which is clearly more accurate than the previous attempts to measure the distance to NGC 55 listed in Table 4.

5. Summary and Conclusions

We have carried out the first Cepheid-based distance determination for the Sculptor Group spiral galaxy NGC 55 from deep images in the optical/near-infrared VIJK bands using our multiwavelength approach used in earlier papers of this series. The resulting distance has a random uncertainty of about 2% and an estimated systematic uncertainty of 4%, not taking account the uncertainty of the LMC distance to which our NGC 55 distance result is tied. Our distance determination is virtually unaffected by the reddening of the NGC 55 Cepheids which we have determined very accurately in our procedure.

In spite of our effort to recognize Cepheids in our database showing clear signs of being blended with nearby stars in our images, and exclude such stars in the distance analysis, it is likely that blending of the remaining Cepheids with non-resolved companion stars is the single most important source of systematic uncertainty in the present study, with an estimated $\sim$3% effect, with this estimation coming from our former HST-based work on NGC 300, where the blending effect on the Cepheid distance was found to be less than 2%. The blending effect in the case of NGC 55 is likely to be somewhat more severe due to the larger inclination of the galaxy with respect to the line of sight.

Our Cepheid distance to NGC 55 is more accurate than the existing distance estimates from the PNLF, TRGB and Tully-Fisher methods, and constitutes another step in our effort to improve the determination of the metallicity dependence of stellar methods of distance measurement, including Cepheids, from comparative analyses of the distances of a set of Local Group and Sculptor Group galaxies in our Araucaria Project. Such studies will be the subject of forthcoming papers.

Within the (small) uncertainties, the Cepheid distances of the Sculptor galaxies NGC 55 and NGC 300 agree. Taking into account the small angular separation of these two galaxies in the sky, the distance of NGC 55 measured in this paper supports the conclusion that both galaxies are physically associated.

WG, GP and DM gratefully acknowledge financial support for this work from the Chilean Center for Astrophysics FONDAP 15010003. Support from the Polish grant N203 002 31/046 is also acknowledged. IS was supported by the Foundation for Polish Science through the Homing Programme. It is a special pleasure to thank the support astronomers at ESO-Paranal for their expert help in the observations, and the ESO OPC for the generous amounts of observing time at VLT allocated to our Large Programme. We thank an anonymous referee for his comments.

REFERENCES

Benedict, G.F., McArthur, B.E., Fredrick, L.W., et al., 2002, AJ, 123, 473

Benedict, G.F., McArthur, B.E., Feast, M.W., Barnes, T.G., Harrison, T.E., Patterson, R.J., Menzies, J.W., Bean, J.L., and Freedman, W.L., 2007, AJ, 133, 1810

Bono, G., Caputo, F., Castellani, V., and Marconi, M, 1999, ApJ, 512, 711

Bono, G., Marconi, M., Cassisi, S., Caputo, F., Gieren, W., and Pietrzyński, G., 2005, ApJ, 621, 966

Bresolin, F., Pietrzyński, G., Gieren, W., and Kudritzki, R.-P., 2005, ApJ, 634, 1020

Fouqué, P., and Gieren, W., 1997, A&A, 320, 799

Fouqué, P., Arriagada, P., Storm, J., Barnes, T.G., Nardetto, N., Merand, A., Kervella, P., Gieren, W., Bersier, D., Benedict, G.F., and McArthur, B.E., 2007, A&A, submitted

Gieren, W., Pietrzyński, G., Walker, A., Bresolin, F., Minniti, D., Kudritzki, R.P., Udalski, A., Soszyński, I., Fouqué, P., Storm, J., and Bono, G., 2004, AJ, 128, 1167

Gieren, W., Pietrzyński, G., Soszyński, I., Bresolin, F., Kudritzki, R.-P., Minniti, D., and Storm, J., 2005a, ApJ, 628, 695

Gieren, W., Pietrzyński, G., Bresolin, F., et al., 2005b, Messenger, 121, 23

Gieren, W., Storm, J., Barnes III, T.G., Fouqué, P., Pietrzyński, G., and Kienzle, F., 2005c, ApJ, 627, 224

Gieren, W., Pietrzyński, G., Nalewajko, K., Soszyński, I., Bresolin, F., Kudritzki, R.P., Minniti, D., and Romanowsky, A., 2006, ApJ, 647, 1056

Hawarden, T.G., Leggett, S.K., Letawsky, M.B., et al., 2001, MNRAS, 325, 563

Jerjen, H., Binggeli, B., and Freeman, K., 2000, AJ, 119, 593

Karachentsev, I.D., et al., 2003, A&A, 404, 93

Kudritzki, R.P., Bresolin, F., and Przybilla, N., 2003, ApJ, 582, L83

Lee, H., Skillman, E.D., Cannon, J.M., Jackson, D.C., Gehrz, R.D., Polomski, E.F. and Woodward, C.E., 2006, ApJ, 647, 970

Madore, B.F., and Freedman, W.L., 1991, PASP, 103, 933

McGonegal, R., McAlary, C.W., Madore, B.F., and McLaren, R.A., 1982, ApJ, 257, L33

Ngeow, C., and Kanbur, S.M., 2006, ApJ, 650, 180

Persson, S.E., Madore, B.F., Krzeminski, W., Freedman, W.L., Roth, M, and Murphy, D.C., 2004, AJ, 128, 2239

Pietrzyński, G., Gieren, W., and Udalski, A., 2002, PASP, 114, 298

Pietrzyński, G., Gieren, W., Soszyński, I., Bresolin, F., Kudritzki, R.-P., Dall'Ora, M., Storm, J., and Bono, G., 2006a, ApJ, 642, 216

Pietrzyński, G., Gieren, W., Soszyński, I., et al., 2006b, AJ, 132, 2556 (Paper I)

Pritchet, C.J., Schade, D., Richer, H.B., Crabtree, D., and Yee, H.K.C., 1987, ApJ, 323, 79

Schlegel, D.J., Finkbeiner, D.P., and Davis, M., 1998, ApJ, 500, 525

Soszyński, I., Gieren, W., and Pietrzyński, G., 2005, PASP, 117, 823

Soszyński, I., Gieren, W., Pietrzyński, G., Bresolin, F., Kudritzki, R.P., and Storm, J., 2006, ApJ, 648, 375

Tikhonov, N.A., Galazutdinova, O.A., and Drozdovsky, I.O., 2005, A&A, 431, 127

Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Woźniak, P., and Żebruń, K., 1998, Acta Astron., 48, 147

Van de Steene, G.C., Jacoby, G.H., Praet, C., Ciardullo, R., and Dejonghe, H., 2006, A&A, 455, 891

Van Leeuwen, F., Feast, M.W., Whitelock, P.A., and Laney, C.D., 2007, MNRAS, 379, 723

This preprint was prepared with the AAS LaTeX macros v4.0.

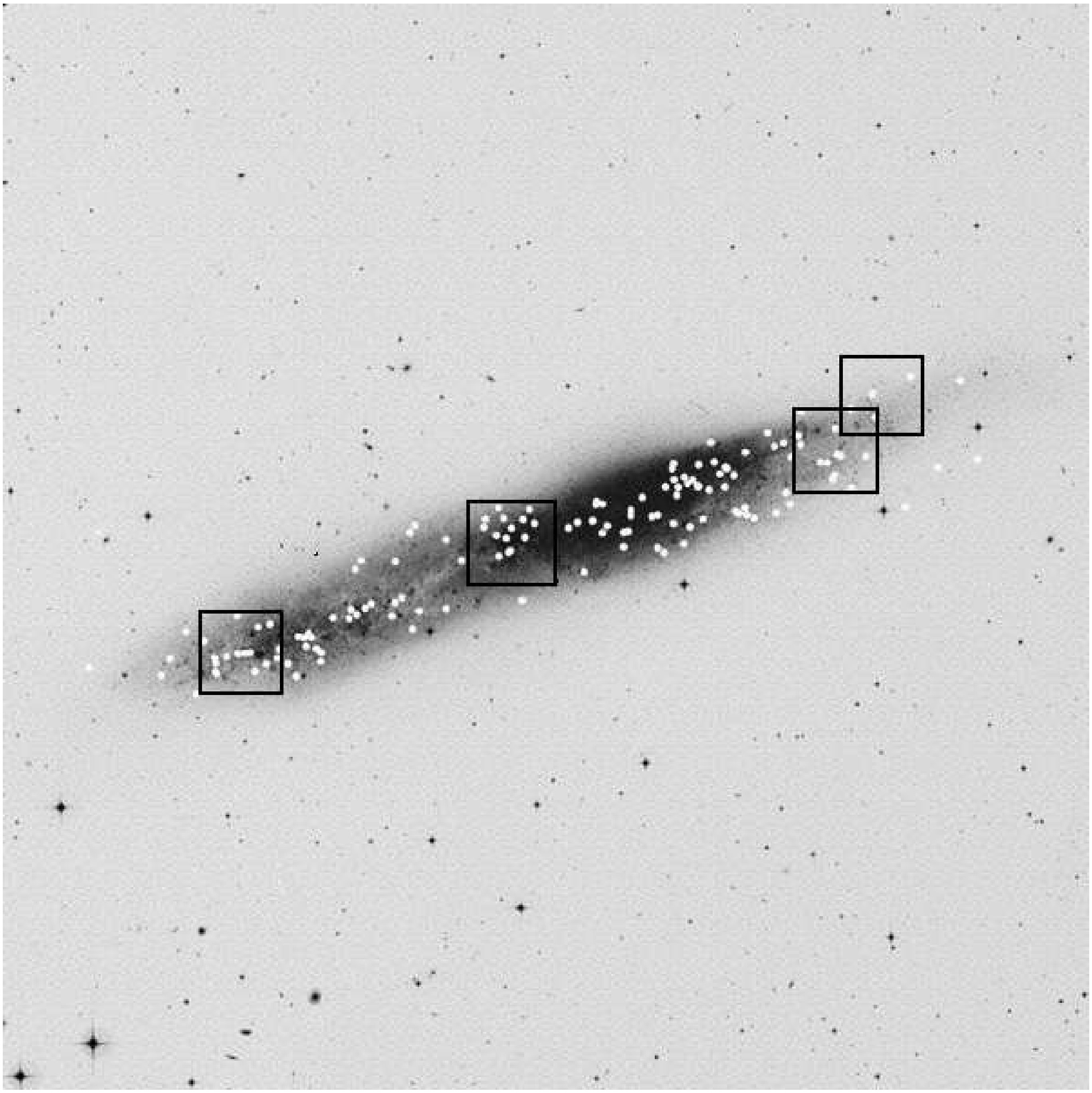

Fig. 1.— The location of the four observed VLT/ISAAC fields in NGC 55 on the DSS blue plate. We observed each field on two different nights. The white dots indicate the Cepheids discovered in our previous optical survey (Paper I).

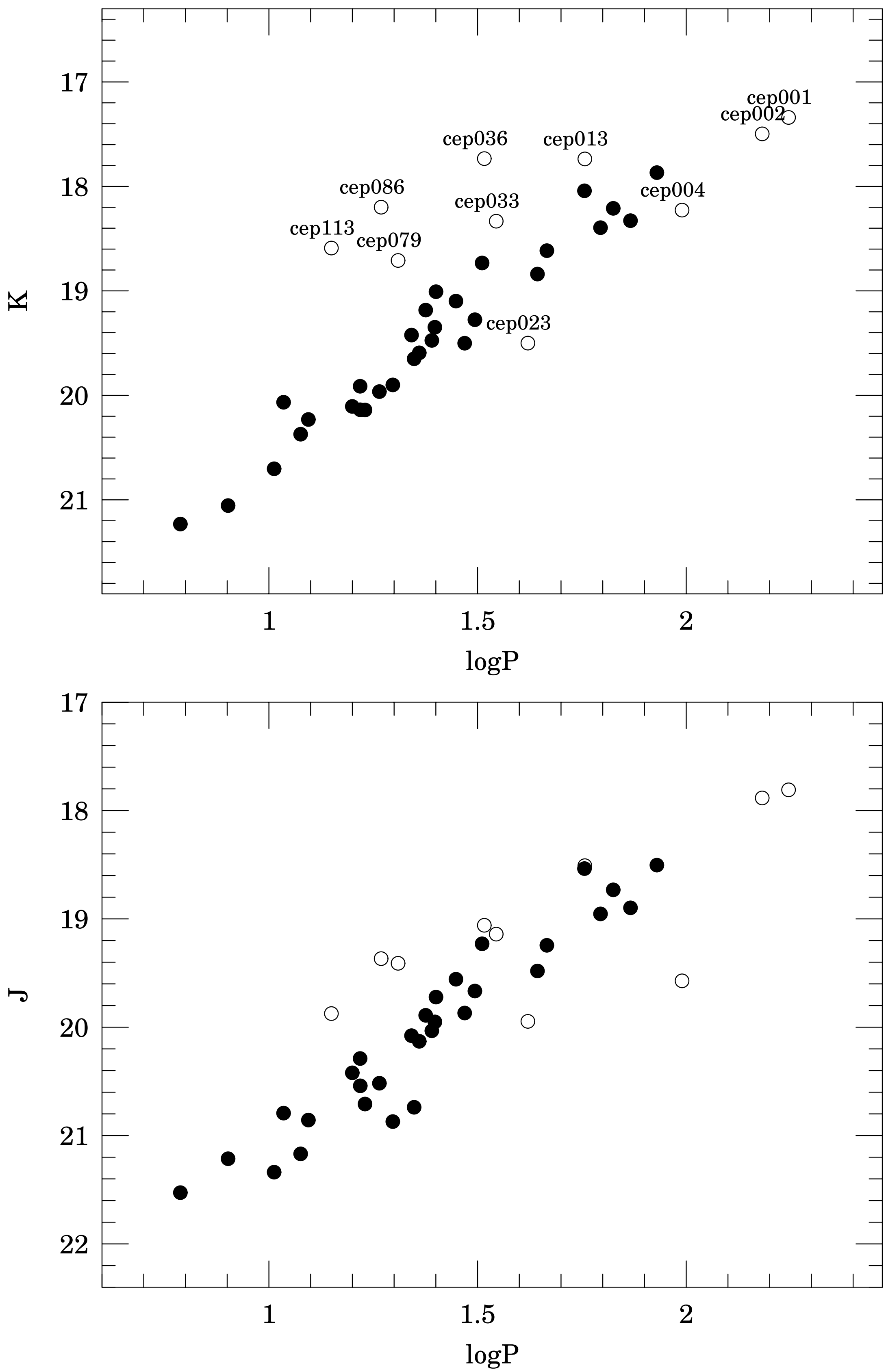

Fig. 2.— The near-infrared J and K band period-luminosity relations defined by the 40 observed NGC 55 Cepheids. Each mean magnitude was derived from two random-phase observations by the method of Soszyński et al. (2005). Stars which were not used in the distance determination (see text) are indicated by open circles.

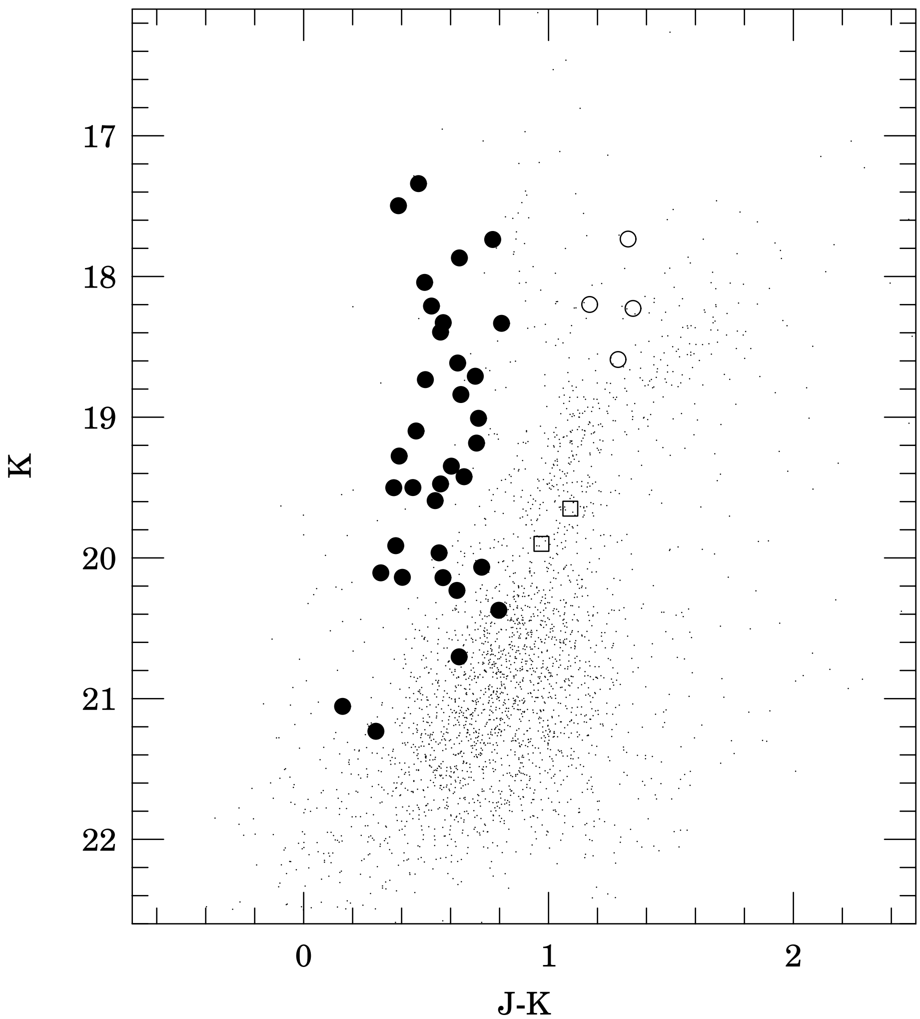

Fig. 3.— The location of the Cepheid variables in NGC 55 in the K, J-K color-magnitude diagram. The bulk of the variables clearly define the instability strip in its expected position (filled circles). Outliers are a group of four very bright and red stars (open circles), which are objects cep004, 036, 086 and 113 in our database. Cepheids 036, 086 and 113 are the most deviating objects in the K-band PL diagram in Fig. 2, supporting our choice to remove these objects in the distance solution. These objects are either heavily blended by very red and bright objects, or they are not classical Cepheids. There are two additional objects located outside the instability strip (open squares), cep69 and cep81. If all six outliers are removed from the database, the remaining Cepheids lying inside the instability strip define PL relation slopes of -2.81 +/- 0.17 in J, and -2.94 +/- 0.20 in K, which are consistent with the LMC PL relation slopes of Persson et al. within 2 sigma.

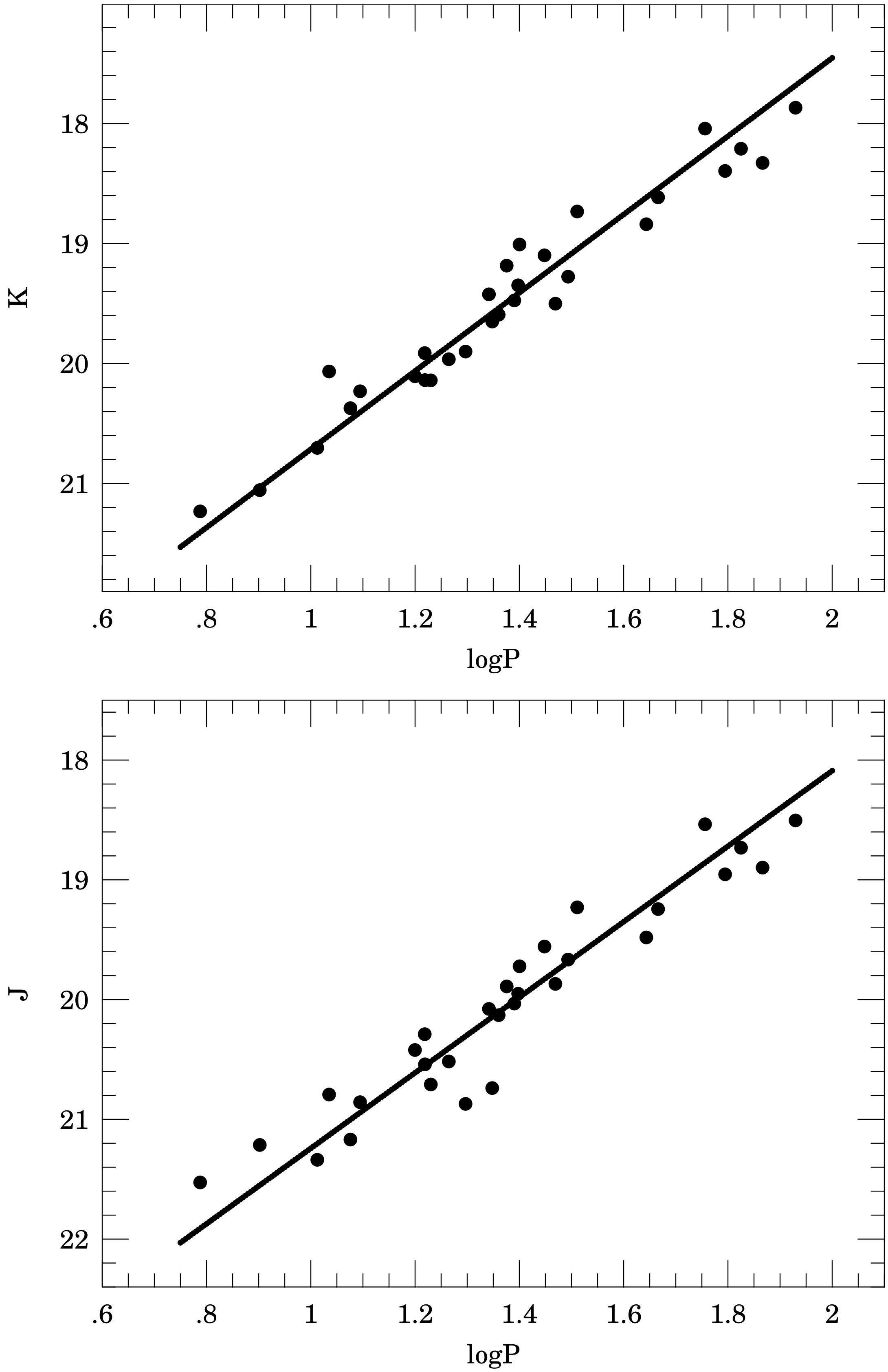

Fig. 4.— Cepheids in NGC 55 adopted for the near-infrared PL solutions, plotted along with the best-fitting lines. The slopes of the fits were adopted from the LMC, and the zero points determined from our data.

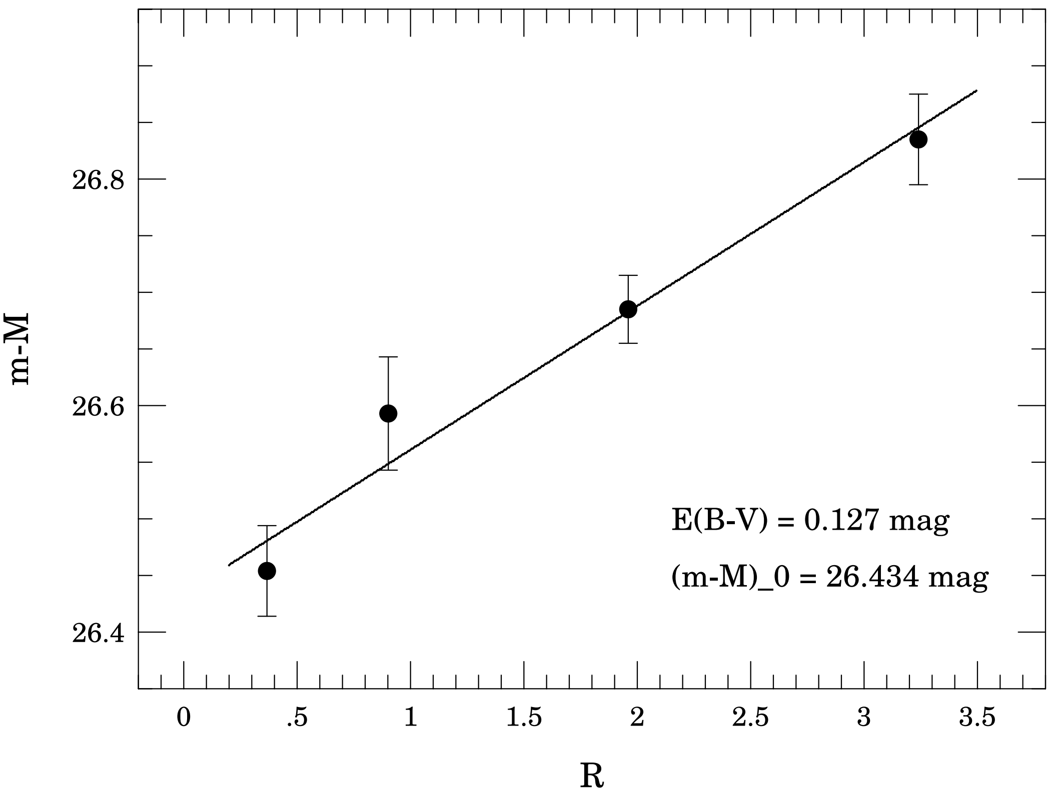

Fig. 5.— Apparent distance moduli to NGC 55 as derived in the VIJK photometric bands, plotted against the ratio of total to selective extinction as adopted from the Schlegel et al. reddening law. The intersection and slope of the best-fitting line give the true distance modulus and the average total reddening, respectively. The data in this diagram suggest that the Galactic reddening law is a very good approximation for NGC 55 as well.

Table 1. Journal of the Individual J and K band Observations of NGC 55 Cepheids

ID	J HJD 2400000+	J mag	σ mag	K HJD 2400000+	K mag	σ mag
cep001	53206.335935	17.751	0.009	53206.260866	17.285	0.013
cep010	53206.335935	18.786	0.014	53206.260866	18.299	0.017
cep013	53206.335935	18.602	0.013	53206.260866	17.798	0.015
cep126	53206.335935	20.992	0.061	53206.260866	20.132	0.072
cep002	53222.266831	17.820	0.024	53222.299022	17.435	0.025
cep004	53222.266831	19.682	0.028	53222.299022	18.259	0.039
cep005	53222.266831	18.389	0.024	53222.299022	17.781	0.023
cep009	53222.266831	18.972	0.021	53222.299022	18.403	0.023
cep012	53222.266831	18.739	0.025	53222.299022	18.232	0.021
cep036	53222.266831	19.170	0.029	53222.299022	17.779	0.044
cep055	53222.266831	19.719	0.031	53222.299022	18.957	0.032
cep072	53222.266831	19.911	0.039	53222.299022	19.336	0.029
cep081	53222.266831	21.152	0.058	53222.299022	19.914	0.060
cep002	53249.278595	17.882	0.022	53249.200628	17.515	0.026
cep004	53249.278595	19.631	0.037	53249.200628	18.298	0.029
cep005	53249.278595	18.634	0.023	53249.200628	17.918	0.023
cep009	53249.278595	18.918	0.022	53249.200628	18.335	0.028
cep012	53249.278595	19.213	0.028	53249.200628	18.536	0.032
cep036	53249.278595	19.126	0.035	53249.200628	17.854	0.027
cep055	53249.278595	19.688	0.036	53249.200628	18.929	0.037
cep072	53249.278595	20.117	0.039	53249.200628	19.308	0.044
cep081	53249.278595	20.734	0.079	53249.200628	20.047	0.120
cep020	53204.306992	19.404	0.026	53204.228037	18.894	0.023
cep023	53204.306992	19.924	0.032	53204.228037	19.510	0.022
cep037	53204.306992	19.149	0.020	53204.228037	18.603	0.016
cep039	53204.306992	19.578	0.040	53204.228037	19.259	0.026
cep079	53204.306992	19.308	0.035	53204.228037	18.469	0.015
cep087	53204.306992	20.296	0.035	53204.228037	19.862	0.027
cep098	53204.306992	20.878	0.046	53204.228037	20.016	0.045
cep100	53204.306992	20.691	0.057	53204.228037	20.306	0.049
cep101	53204.306992	20.168	0.048	53204.228037	19.850	0.030
cep138	53204.306992	21.015	0.095	53204.228037	20.828	0.067
cep020	53223.250368	19.430	0.020	53223.275357	18.702	0.027
cep023	53223.250368	19.909	0.023	53223.275357	19.456	0.034
cep037	53223.250368	19.267	0.014	53223.275357	18.850	0.024
cep039	53223.250368	19.796	0.027	53223.275357	19.354	0.033
cep069	53223.250368	20.831	0.075	53223.275357	19.645	0.068

Table 2. Intensity mean J and K magnitudes for 40 Cepheid variables in NGC 55

ID	P days	$< J >$ mag	$\sigma_{\rm J}$ mag	$< K >$ mag	$\sigma_{\rm K}$ mag
cep001	175.9086	17.809	0.027	17.340	0.028
cep002	152.0943	17.884	0.034	17.497	0.036
cep004	97.7291	19.572	0.041	18.227	0.042
cep005	85.0550	18.504	0.034	17.868	0.034
cep009	73.5323	18.898	0.033	18.328	0.036
cep010	66.8528	18.732	0.029	18.210	0.030
cep012	62.3186	18.954	0.036	18.395	0.037
cep013	57.1544	18.509	0.028	17.737	0.029
cep014	57.0377	18.536	0.035	18.042	0.032
cep018	46.3493	19.244	0.038	18.615	0.035
cep020	44.0077	19.481	0.034	18.839	0.035
cep023	41.7395	19.946	0.037	19.500	0.038
cep033	35.0516	19.141	0.037	18.333	0.031
cep036	32.8210	19.059	0.041	17.734	0.044
cep037	32.4267	19.230	0.030	18.733	0.032
cep039	31.1574	19.666	0.042	19.276	0.039
cep043	29.4512	19.869	0.050	19.501	0.036
cep044	28.0657	19.557	0.045	19.098	0.044
cep055	25.1401	19.722	0.042	19.008	0.043
cep056	24.9857	19.951	0.033	19.348	0.036
cep057	24.5666	20.033	0.043	19.474	0.042
cep059	23.7508	19.890	0.043	19.184	0.043
cep064	22.9247	20.130	0.042	19.593	0.038
cep069	22.2824	20.739	0.079	19.650	0.072
cep072	21.9627	20.078	0.046	19.423	0.045
cep079	20.3942	19.410	0.038	18.709	0.033
cep081	19.8080	20.871	0.074	19.900	0.098
cep086	18.5752	19.367	0.031	18.199	0.034
cep087	18.3966	20.517	0.039	19.964	0.041
cep098	16.9912	20.709	0.049	20.140	0.085
cep100	16.5556	20.541	0.051	20.138	0.055
cep101	16.5403	20.289	0.047	19.913	0.042
cep103	15.8413	20.421	0.054	20.106	0.057
cep113	14.1150	19.874	0.052	18.590	0.053
cep122	12.4326	20.857	0.060	20.231	0.056
cep126	11.9130	21.169	0.074	20.372	0.076
cep129	10.8421	20.793	0.047	20.066	0.076

Table 3. Reddened and Absorption-Corrected Distance Moduli for NGC 55 in Optical and Near-Infrared Bands

Band	V	I	J	K	$E(B-V)$
$m-M$	26.835	26.685	26.559	26.439	–
R_λ	3.24	1.96	0.902	0.367	–
$(m-M)_0$	26.423	26.436	26.444	26.392	0.127

Table 4. Table 4. Previous Distance Determinations to NGC 55

Distance [Mpc]	Method	Reference
1.34 +/- 0.08	Carbon stars	Pritchet et al. 1987
1.8 +/- 0.2	Tully-Fisher	Karachentsev et al. 2003
2.12 +/- 0.10	TRGB	Tikhonov et al. 2005
2.30 +/- 0.35	PNLF	Van de Steene et al. 2006
1.91 +/- 0.10	Cepheids, VI	Pietrzynski et al. 2006b
1.94 +/- 0.08	Cepheids, VIJK	this paper